Technical report

Integrating bio-physical and socio-economic criteria for mapping rainwater management strategies at landscape scale

Authors : Catherine Pfeifer, An Notenbaert, Yenenesh Abebe, Abisalom Omolo

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# Introduction

Most farmers in the humid parts sub-Saharan Africa depend mainly on unreliable rain fed agriculture and are vulnerable to climate variability. The main issue is not the lack of water as such, but its temporal distribution. The lack of appropriate water management in these areas prevents smallholders from addressing the consequences of flooding during the rainy season and droughts during the dry season. This is a major contributory factor to the food insecurity and poverty that prevail in the region (Hanjra and Gichuki, 2008; De Fraiture et al., 2010).

Predictions of population growth (UNFPA, 2011) and of extreme weather conditions due to climate change suggest that the pressure on these already vulnerable regions is likely to increase (Rosenzweig et al., 2001; Mirza, 2003). These trends reinforce the necessity to focus on agricultural water management as a starting point to improving the livelihoods of communities who depend on rain fed agriculture.

Whereas in the past the focus of water management was mainly on surface water, the concept of integrated rainwater management has now started to emerge. This is a holistic concept that abandons the differentiation between irrigated and rain-fed agriculture (Rockström et al., 2003, 2010; Humphreys et al., 2008). This approach seeks to manage agricultural systems by simultaneously addressing issues with land and water and taking into account the demands of crops, trees and livestock. This approach allows smallholders a range of choices of how to improve water management on their farm. We define a rainwater management practice (RMP) as any activity that smallholders reliant on rain water can apply on their farms to improve water availability or water productivity.

Nowadays, there is a general understanding that “blanket approaches” do not work and that RMPs need to be well targeted to the bio-physical, socio-economic and institutional context (Wood et al., 1999; Merrey and Gebreselassie, 2010). Consequently there is a need for better geographical targeting tools that identify suitable locations for a given intervention. Even when the suitability of a single RMP to its location is relatively well understood, the extent of the area to which it is appropriate has only rarely been mapped out. As a result, policy-makers and development and extension workers tend to promote blanket approaches and sometimes promote practices in unsuitable locations.

A broad body of research over the last decade resulted in a relatively good understanding of the bio-physical suitability criteria for RMP (Desta et al., 2005; Merrey and Gebreselassie, 2010) in the Ethiopian context. Yet, most geographical targeting approaches for resource management fail in taking socio-economic and institutional context into account. Indeed, socio-economic studies sometimes contradict themselves and consequently, defining clear suitability ranges or weights for aggregation into a single contextual geographical layer is difficult.

Finally, the integrated watershed management approach also implies that the combination of two or more RMPs can generate beneficial synergies within a landscape or a watershed. Although this implication is well understood, there are few modeling approaches that are able to handle combinations of RMPs.

The objective of this report is to present a modeling framework that maps combinations of RMPs, allowing us to identify where a particular RMP is suitable and which other RMPs it should be combined with to generate synergies. It also presents a novel way to account socio-economic constraints in a spatially explicit way. Also this paper discusses how the created maps can be linked to hydrological models like SWAT for hydrological impact assessment.

This research is part of the Nile Basin Development Challenge Program (NBDC) funded by the challenge program for water and food (CPWF) and therefore the whole framework has been applied to the Ethiopian Blue Nile Basin. The following section presents the major concepts used for modeling rainwater management at the landscape scale. The section after that describes the data used for the mapping as well as the modeling framework. It discusses how “willingness of adoption” maps that capture the socio-economic constraints can be build and how different practices can be aggregated at landscape scale. Also, this section explains how the maps resulting from the presented modeling frameworks need to be adjusted so that the maps can feed into hydrological models such as SWAT (Santhi et al., 2006). The fourth section discusses the application to the Blue Nile, the modeling of the best bet practice and the strategies. Finally the report ends with a technical discussion section and conclusions.

# Concept and definitions

In this paper, RMPs are understood as any water management technology or practice that can be adopted by a smallholder on his or her plots or farm. As such, RMPs include a broad range of practices. Aside from traditional water related technologies, they encompass practices related to crops, livestock and trees which contribute to water availability or water productivity (Molden, 2007) on the smallholder’s own plot, (i.e. at the farm scale) or on a number of plots within the watershed (the landscape scale).

## Rainwater management practices

As land is inextricably linked with water; every land-use decision is also a water decision (Bossio et al., 2010). Some activities that might therefore be seen as land management practices are also RMPs. For example, building terraces and bunds can reduce soil erosion, but also increase water infiltration, making rainwater available for a longer period for crops.

Agroforestry practices, such as planting trees along contours or in fields, also increase water infiltration, reduce run-off and control erosion. The use of trees that serve several purposes such as providing fodder, fruit, fuel wood and timber, or which increase fertility through binding nitrogen, are of particular interest to farmers (Reubens et al., 2011), as they can provide multiple benefits in addition to water management. Whereas agro-forestry might have little impact on water productivity at the farm level, it can stabilize water availability in downstream locations, increasing availability when it is most needed, in the dry season (Garrity et al., 2010).

Water harvesting and small-scale irrigation from rivers or groundwater can also increase water availability on farms. While these practices may well increase production at the farm level and improve the smallholder’s livelihood they can also have downstream effects, which need to be considered.

Conservation agriculture, which includes minimal tillage and the use of mulch, increase water infiltration and reduce evapotranspiration (Rockström et al., 2003). Limiting livestock movements reduces soil compaction and also increases infiltration (Descheemaeker et al., 2009). Improved fertility management, which can include the use of artificial fertilizers, composting and crop rotation, can also contribute to increased water productivity, as it increases agricultural production per unit of water used. The use of improved seeds (such as drought resistant crop varieties) or improved livestock breeds (such as cross-breed cows) can have similar effects. All these practices have the potential to contribute to better rainwater management.

Finally, we need to consider the concept of livestock water productivity. This is a measure of the ratio of animal product, or its value, to the water used to produce it (Descheemaeker et al., 2009). Most of the water ‘consumed’ by livestock is actually used for growing fodder rather than for drinking. Therefore, it is also important to address the whole range of practices that can improve the water productivity of fodder production. These include all the fodder crop related practices as well as better grassland management. Over-sowing, which involves planting high-protein grass to improve fodder quality, is one example of this. Zero-grazing system (also referred to ‘cut and carry systems’), in which livestock is kept in barns, is another. It reduces the animals’ nutritional needs and increases water productivity.

## Integrated rainwater management in a landscape

The implementation of individual RMPs in isolation might not generate many overall benefits. Some of these practices can also have impacts, positive or negative, on downstream farmers. It is therefore essential to take account of potential synergies and optimize rainwater management at the landscape scale rather than the farm scale.

The landscape approach to rainwater management focuses on a watershed that contains a variety of land uses. These will vary between top slopes (upland), middle slopes (midland) and the valley bottoms (lowland). The landscape approach needs to be jointly managed by its inhabitants. A rainwater management strategy (RMS) will combine a range of RMPs that cover the whole slope gradient of the landscape and optimize water availability or water productivity throughout the whole watershed. This approach does not focus on the individual, heterogeneous, elements of the landscape but, rather, aims to develop the maximum synergies between the different practices within the landscape.

Each of the RMPs adopted in each of the landscape zones will need to meet different objectives. By maximizing the potential synergies and minimizing any negative trade-offs between these individual RMPs the aim is to maximize the water availability and productivity at the landscape scale. This rationale informs the choice of site-specific strategies. Table 1 shows examples of RMPs in each zone with their specific objectives. Combinations of these RMPs then form RMSs with an overarching goal of increasing the overall water productivity or water availability in the watershed.

Table 1 : Objectives of different land uses in each landscape zone with examples of RMPs in italic

|  |  |  |  |
| --- | --- | --- | --- |
| Zone\Land use | Main objective (*examples*) | | |
| Cropland | Grassland | Degraded land |
| Uplands | Increase infiltration  *Agroforestry(such as orchards and multipurpose trees)* | Increase the quantity and quality of fodder for livestock  *over-sowing, limiting animal movements* | Rehabilitate degraded land  *Forestry* |
| Midlands | Control erosion, maintain soil moisture  *Soil and water conservation (terraces and bunds)*  *Agroforestry*  *Conservation agriculture* |
| Lowlands | More efficient use of surface or shallow groundwater  *Wells, river diversion* |

In the uplands the objective will largely be to increase water infiltration through agroforestry and forestry. The midlands are usually relatively hilly and the aim is to control erosion and maintain soil moisture through in-situ soil and water conservation, or through conservation agriculture and/or agroforestry. In the lowlands water is usually available, either as groundwater or in rivers. The objective in this zone will be to increase the productivity of surface and shallow ground water. Rainwater management in the grasslands and on heavily degraded land will have particular objectives, regardless of the landscape zone. On grasslands, it is important to improve the quantity and quality of the fodder, whereas on heavily degraded land, rehabilitation is the major objective. Finally, fertility management and *ex-situ* rainwater harvesting can potentially be applied everywhere, regardless of biophysical conditions. Because of this, we did not look at these practices in the mapping exercise described below. This does not imply that they are not important elements of rainwater management but they can be combined with any RMP, regardless of location.

# Materials and methods

## Existing geographical layers

There are many geographical layers (geodata) available for Ethiopia, which cover a variety of biophysical characteristics. For this modeling exercise, we used the following layers presented in (Pfeifer et al., 2012)

Table 2 : geographical layers used

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Geographical layer | Description | Resolution | Year | Reference |
| Annual rainfall | Average rainfall 1950-2000 | 1 km | 2000 | Worldclim |
| Mean temperature | Average temperature 1950-2000 | 1 km | 2000 | World clim |
| Minimum temperature | Average minimum temperature 1950-2000 | 1 km | 2000 | World clim |
| Aridity index | Mean Annual Aridity (annual average over the period of 1950-2000) | 1 km | 2000 | Worldclim |
| Elevation | Corrected elevation map | 90x90 | 2008 | SRTM |
| Slope | Based on elevation map |  |  |  |
| Topographic index | Based on elevation map |  |  |  |
| Soil map | Master plan of the Blue Nile | 1:250 000 |  | Ministry of Water and Energy |
| Land use | Master plan of the Blue Nile | 1:250 000 |  | Ministry of Water and Energy |
| rivers | Perennial and non-perennial rivers of Ethiopia | 1:2000000 | 2005 | (USAID, 2005) |
| Groundwater | Based on the geological subtract | 1:250 000 | 2012 | (Kebede, 2012) |
| Land degradation | Based on satellite image | 0.05 deg | 2008 | (Bai et al., 2008) |
| Ethiopian rural economic atlas | Census data from the Ethiopian agricultural survey | Woredas |  | (-, 2006) |
| Travel time | Time to market | 1 km | 2008 | (Nelson, 2008) |
| Major towns | Town >10 000 inhabitant | 1:2000000 |  | (UNOCHA 2007) |
| Distance to major town | Build based on major towns |  |  |  |
| Aridity index |  | 1 km |  | (Trabucco and Zomer, 2009) |
| FAO watershed | Based on slope | Watersheds | 2003 | (FAO, 2003) |
| N4 watershed | Watershed developed for SWAT | Watersheds | 2012 | (Seyoum, 2012) |

## Willingness of adoption maps

A broad body of research over the last decade resulted in a relatively good understanding of the bio-physical suitability criteria for RMP (Desta et al., 2005; Merrey and Gebreselassie, 2010) in the Ethiopian context. With the increased spreading of Geographical Information Systems (GIS) and geographical data, creating suitability maps showing areas where all bio-physical conditions are met has therefore become easy (Wood et al., 1999). Also open-source solutions that do not require any GIS skills are made available (Quiros et al., 2009).

Yet, most geographical targeting approaches for resource management fail in taking socio-economic and institutional context into account. Indeed, socio-economic studies sometimes contradict themselves and consequently, defining clear suitability ranges or weights for aggregation into a single contextual geographical layer is difficult.

The approach chosen for this paper is to create a geographical layer that summarizes the socio-economic context for rainwater management practices in the form of “willingness to adopt maps”. These maps can be constructed with a small area estimation technique, a technique that is usually applied to income model in order to assess poverty (Davis, 2003; Hyman et al., 2005). In most simple words, it extrapolates results from a linear econometric model based on a farm household survey to broader scales by predicting the model with full coverage census data. Two major challenges emerge when this technique is not applied to poverty mapping. Firstly, modeling adoption of RMPs in a spatial context raises the issues of the correct specification of the adoption model used as a base to define the econometric model. Secondly, poverty can usually be assessed with linear regression models. Adoption data is by its nature a non-linear process and therefore the approach needs to be adapted to non-linear settings.

A whole range of adoption models exist, from simple static models assessing if a practice is adopted or not, to more dynamic models that take diffusion of technology into account or model duration of adoption of a given practice (Feder and Umali, 1993). For the purpose of adoption maps, the static adoption model are the most appropriate, as there models are relatively simple and can be used for extrapolation in a spatial context.

Classical economic theory suggests that adoption is driven by labor, financial capital and human capital (Ellis, 1993; Sadoulet and de Janvry, 1995). These classical adoption models are usually extended with household characteristics and other control variables that are drivers that are expected to influence adoption suggested by literature. As adoption data is usually in binary from, it needs to be assessed with non-linear econometric approaches such as probit or logit models (Feder and Umali, 1993). The economic model therefore takes the following form : where y is a binary variable that takes value 1 if the given RMP is adopted and zero otherwise, L is labor, K is capital, C are all other control variable variables. The prediction of these models can then be interpreted as willingness of adoption and captures the socio-economic context for successful adoption.

Most of the econometric models simply ignore location : the systematic error is absorbed by the constant and the random error is absorbed by the random error (Anselin, 2001; LeSage and Pace, 2009). When the error is correlated with the explained variable it also results an omitted variable bias (LeSage and Pace, 2009). Different approaches exist to introduce the spatial context into econometric models : inclusion of bio-physical variables into a geo-referenced farm household survey (Pfeifer et al., 2009), introduction of a spatial trend or the use of spatial econometric models (Anselin, 2001).

For mapping adoption, the adoption model chosen needs to be compatible with a small area estimation techniques. Spatial econometric models do not fulfill this criterion. Indeed, these models contain an auto-regressive element, also referred to as weighting matrix to capture characteristics from neighboring agents, that at current stage cannot be predicted in a spatially explicit way (Pfeifer, 2011). Therefore, models for mapping willingness of adoption can only cope with the spatial context by introducing bio-physical variable or a spatial trend.

Introducing bio-physical characteristics as control variable into an econometric model is not trivial. Firstly these models assume that the different explanatory variables are uncorrelated, which is not the case for most bio-physical variables. For example temperature and elevation are often inversely correlated. Patterns of different bio-physical variables therefore need to be analyzed carefully before being introduced as control variable (Pfeifer et al., 2009). Technically, bio-physical data might have been collected within the farm household survey, or can be added ad-hoc with GIS tools, by overlaying geographical layers with the geo-referenced farm household survey. When there is little rational on choosing specific bio-physical variables, or when the geographical layers are not available to retrieve the bio-physical variables, a spatial trend can be introduced into the model : it captures spatial variation without explaining it. Technically, the spatial trends can be accounted for by including the geo-coordinate into the explanatory variables.

Secondly, bio-physical characteristics are introduced into econometric models based on the assumption that the environment influences the decision making. They allow answering the question “what are the drivers of adoption” and increasing significantly the explanatory power of the model. However, geographical targeting calls for a slightly different question, namely “why do some agents adopt a practice on a suitable location while others don’t?” This leads to a slightly different specification of the spatial variables. Instead of introducing them into the adoption model, they are used to constrain the sample of observations. They allow selecting smallholders located on suitable locations only. In other words, traditional econometric models will suggest that smallholders living on a slope are more likely to have soil and water infrastructure than those living in the plain, whereas models for geographical targeting will only consider farmers on the slope, where it makes sense to have this type of infrastructure.

## Specification of the small area estimation for adoption models

### Specification of the adoption model

The adoption model used is the following : where Y is the binary variable that capture the adoption of a given RMP, Φ is the cumulative normal distribution, X the vector of explanatory variable and β the regression coefficient.

Three best bet RMPs for the Ethiopian Blue Nile have been chosen to illustrate the approach, namely orchards, terraces and river diversions. These three RMPs are part of the mostly promoted RMPs by GIZ and are also commonly chosen by stakeholders and communities in participatory processes.

The vector X contains proxies for the different variables in the model. Because this model will be used with a small area estimation technique, variables retained in this model must also be available within the farm census data (Rural economic Atlas) or as geographical layer. This is a very limiting factor, as usually farm household surveys are much richer than census data. Nonetheless, proxies for labor, capital and control variables including the household characteristics and the locational variables need to be found from this list.

For assessing RMPs in the Blue Nile Basin, labor has been approximated with a household density variable, a ratio between household size and land, as well as with a binary variable that captures if the household hires labor and a binary variable that captures if a household member works at least partially outside the farm. Capital has been assessed with landholding size. For household characteristics, the number of plot, access to credit and access to extension services have been retained. Finally access to markets is available within the farm household survey and has been retained as locational variable. Also slope and level of land degradation are available within the farm household survey. As they define the suitability of terraces and orchards, these variables are not introduced into the regression equation but are used to constrain the sample to farm household on suitable locations only. As the farm household survey is geo-referenced, the coordinate of the farm household can be introduced in order to account for the spatial trend.

### Prediction rules

The estimation of the econometric model results into an estimated coefficient that can be used to predict the model : . Whereas the prediction usually uses the variable from the farm household survey, small area estimation technique makes use of census data. The IFPRI rural economic survey based on the census data, gives all the values at woreda (district) level. For the spatial layers that are not within the census data, namely access to market, a zonal statistic is performed to get an average at woreda level.

The prediction based on this approach results in an average willingness of adoption for a given woreda. In principle it would be possible to capture heterogeneity within each woreda by simulating individual farm households. For each woreda, random points corresponding to the amount of rural household could be drawn. For each random point farm household characteristics (X) are simulated based on the average and standard deviation observed at woreda level. For this paper, this approach could not be chosen, as it was not possible to access the woreda level standard deviations.

Also these predictions ignore the residual, which by construction has the value zero. It implicitly assumes that there is no spatial autocorrelation. However, most spatial data are likely to be spatially correlated and therefore the prediction biased. Geo-statistical approaches address this issue by explicitly introducing the residual from the model into the prediction (Pfeifer, 2011). This approach assumes that it is possible to create a residual[[1]](#footnote-1) map, which is the case when one has a full coverage farm household survey or the spatial sampling of the interviewed farm is random. Unfortunately, the farmers in the household survey used in this paper have been sampled with 21 different villages and with this data poor setting, it is not feasible to come up with a meaningful residual map.

## Results for the adoption model

Probit estimations have been fitted for the 6 RMPs, namely orchards, soil and water conservation and wells, in two different type of models : once without spatial trend and once with spatial trend (i.e. the models includes the coordinates).

### Economic model without spatial trend

**Table 3 : results from the probit estimation for the orchard soil and water conservation and irrigation from the river**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Variable at farm level (farm household survey) | Orchard | SWC | Irrigation from the river | Variable at woreda level |
| Landholding size | -0.3633014  (0.002) | -0.32609  (0) | 0.8432849  (0.001) | Average landholding size\* |
| Landholding size square | 0.0098738  (0.469) | 0.025805  (0.031) | -0.1226992  (0.006) |  |
| average plot size | 2.875819  (0) |  | -1.460356  (0.01) | Average plot size\* |
| number of plots |  | 0.077025  (0) | 0.0933675  (0.001) | Land fragmentation\* |
| Household size/landholding size |  |  | 0.0124864  (0.018) | Population density\* |
| female headed HH (binary) |  |  | -0.9771629  (0.001) | Proportion of female headed household\* |
| Has off-farm income (binary) |  | 0.324617  (0.027) |  | Proportion of households not solely dependent on agriculture\* |
| Has hired labor (binary) | 0.0038905  (0) |  |  | Proportion on household who hired labor\* |
| Access to advise from the extension service (binary) | 0.0038905  (0) | 0.390598  (0) |  | Proportion of household with access to extension service\* |
| access to credit (binary) |  |  | 0.3168265  (0.008) | Proportion of households with access to credit services\* |
| time to market |  |  | -0.108154  (0.01) | Travel time\*\* |
| time to market sq |  |  | 0.0017995  (0.041) |  |
| distance to market | 0.723262  (0.001) |  |  | Distance to town with more 10 000 inhabitant\*\* |
| distance to market squared | -0.0015395  (0.023) |  |  |  |
| Constant | 0.5559211  (0.036) | 0.088009  (0.586) | -4.648007  (0) |  |
| Observations | 683 | 724 | 814 |  |
| R-squared | 0.1073 | 0.096 | 0.1111 |  |
| Condition | slope>0 | erosion>0 | at least one flat plot |  |
| p-value in bracket  \*taken from the Ethiopian Rural Economic Atlas (census data)  \*\* other geographical layer (see data description in table 2) | | | | |

Willingness of adoption for orchards has been assessed with a sample of farmers that do have plots on a slope, where agro-forestry contributes to water infiltration in the landscape. Orchards are more likely to be found with households that have smaller landholdings. Despite of the positive sign of the squared landholding, the overall impact of increasing landholding stays negative over the relevant range of landholding size (< 3 ha). Also farmers who have bigger plots size, who hire labor and have access to advise are more likely to adopt orchards. Also orchards are found further away from markets. Indeed despite of the positive sign of the squared distance to market, the distance to market increases the probability of adoption of orchards. As fruits are usually sold on markets, this result might look contra-intuitive. But it can be explained by the fact that orchard has been defined as mango, papaya and coffee, all products that do not need to reach market rapidly, and for which usually the middle man comes to the farm rather than the farmer going to the market. Also in very remote areas, orchards are promoted to increase food security and fruits are mainly used for home consumption. Also note that the farm household survey did not contain any farmers with apple trees. Indeed, apple trees have only very recently been promoted in selected locations.

Adoption of soil and water conservation is estimated on a sample of farmers that have plots on degraded land (i.e self-assessed erosion contained in the farm household survey), where these measures are necessary. Soil and water conservation seems to be adopted by smallholders with smaller holdings over the relevant range (< 3 ha) but who have more plots. Farmers with off farm jobs and who hire labor are more likely to have soil and water conservation practices. This suggests that smallholders who earn money outside of the agricultural sector can afford hiring labor to do the labor intensive work needed for constructing these structures. Also access to advice through the extension services, allowing to acquire knowledge on how to build these structures increase the adoption rate.

**Table 4 : results from the probit estimation for multipurpose trees, water harvesting and wells**

|  |  |  |  |
| --- | --- | --- | --- |
| Variable at farm level (farm household survey) | Multipurpose trees | Water harvesting | Wells |
| Landholding size | 1.171068 | -0.80916 | -0.2998654 |
|  | 0 | 0 | 0.015 |
| Landholding size squared | -0.2308554 | 0.077981 |  |
|  | 0.001 | 0 |  |
| number of plots |  | 0.072851 | 0.0793784 |
|  |  | 0.013 | 0.012 |
| Has off-farm income (binary) | 0.1476533 |  | 0.9268875 |
|  | 0.043 |  | 0 |
| Has hired labor (binary) | 0.0108987 |  |  |
|  | 0.017 |  |  |
| Access to advise from the extension service (binary) | 0.5137062 |  | 0.5348329 |
|  | 0 |  | 0.021 |
| distance to market |  |  | 0.477516 |
|  |  |  | 0.001 |
| distance to market sq |  |  | -0.0583435 |
|  |  |  | 0.002 |
| Constant | -3.379912 | -1.27183 | -3.085245 |
|  | 0 | 0 | 0 |
| Observations | 683 | 997 | 815 |
| R-squared | 0.0921 | 0.1088 | 0.2157 |
| Condition | slope>0 | no | at least one flat plot |

Irrigation from the river usually takes place within 3 km around a perennial river and entails irrigation from the river with a pump and river diversion. As no accurate map of perennial rivers in Ethiopia exist, the sample has been constraint for farmers having plots in flat areas, as crop land near to the river are in general flatter. Irrigation from the river increases as landholding increases up to 7ha. Beyond 7 ha, landholding size will have a negative effect on the adoption of irrigation from the river. Also farmers with more but smaller plots and bigger land pressure (household size / landholding) are more likely to irrigate from the river. Female headed household are less probable to irrigate from the river. This can be explained by the fact that female headed household often have less negotiation power and therefore face more difficulty in accessing the river water and are often too poor to afford a pump. As travelling time to markets increases (over the relevant range <30 hours) the adoption of irrigation from the river decreases. This expected result can be explained by the fact that irrigated plots are often used to grow high value cash crop like horticulture, which products need to reach the market relatively fast.

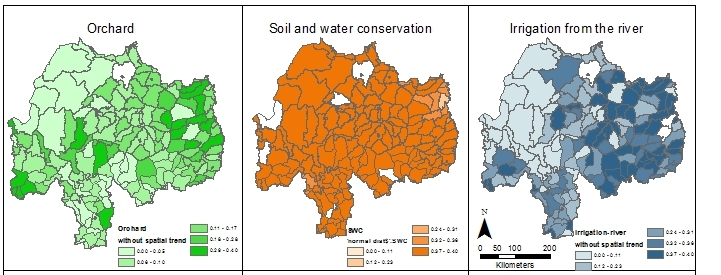
Multipurpose trees have been estimated for farmers who have at least one field which is not flat. Farmers with bigger landholdings up to 5ha are more likely to adopt multipurpose trees. Beyond the 5ha threshold, farmers are less likely to adopt multipurpose trees as their landholding increases. Also smallholders with off-farm income that hire labor and have access to extension services are more likely to adopt multipurpose trees.

Adoption of water harvesting has been assessed without constraining the sample, as it is potentially suitable everywhere. Only for farmers with landholding sizes bigger than 10ha, adoption of rainwater harvesting increases with landholding size. This suggests that very small farmers and large commercial farmers are more likely to adopt water harvesting technologies. Indeed, commercial farmers have sufficient capital to invest into big water harvesting ponds. Very small farmer might collect rainwater from the roof for domestic use or for livestock. Also farmers with more plots are more likely to adopt a rainwater harvesting technology.

Estimations for wells have been constrained to farmers that have at least one plot in a flat area. Wells are more likely to be adopted by farmers with small landholding size but with a bigger number of plots. Also farmers with off-farm income and with access to advice have a higher adoption rate. Indeed, quite a lot of knowledge about groundwater is needed for digging a well at the right location and it is a quite expensive procedure. Paradoxically, farmers that are further away from markets are more likely to have wells. The only explanation is that this result might be distorted because many farmers cannot have wells as groundwater is too far away. As no reliable groundwater map is available, it is not possible to constrain the sample to farmers who have access to groundwater. Also only about 40 farmers have adopted wells in the sample, which might not be sufficient to reach statistical convergence.

Note that the models have a relatively low explanatory power (R-squared). Many location characteristics have not been included in the model, such as slope, degradation and rainfall, which could significantly improve these models. These variables would capture the bio-physical context rather than adoption itself and are included in the modeling approach with the bio-physical suitability maps. Some of these variables have been used as constraints to assess the adoption of farmers on suitable locations only.

The coefficient of the regressions shown in Table 3 and 4 can be used to predict the probit model from full coverage census data (Rural economic Atlas) and geographical layer described in the last column of the table. The resulting average willingness of adoption at woreda level can be mapped out (Figure 1). As woreda level data is used for the extrapolation, the adoption rate is an average for the woreda and can be interpreted as average willingness to adopt. However, adoption is in this case not site-specific and does not take variability of households into account.



**Figure 1 : willingness of adoption at woreda level, in the Ethiopian Blue Nile Basin, based on probit estimation without trend**

Willingness to adopt orchards are higher in East of the basin, with a spatial trend through the center of the basin. Soil and water conservation is predicted relatively high in the whole basin. Only the very North East shows slightly lower adoption rate. As the explanatory power of the probit model behind this map is very low, interpretation of this map is difficult. Finally irrigation from the river is found mainly in the East of the basin as well as in the South West.

D:\Ilri\final technical report\adoption maps well.tif

**Figure 2 : willingness of adoption at woreda level, in the Ethiopian Blue Nile Basin, based on probit estimation without trend**

Multipurpose trees are adopted mainly in the South west, whereas water harvesting is more likely to be adopted in the North East and in the very West, which are also the dryer zones of the basin. Finally wells are more likely to be adopted in the west of Tana Lake as well as in the center of the basin.

### Models with spatial trend

The models run in the previous section do not include explicitly any spatial component. Models with spatial trend, i.e. models that include the coordinates, can account for spatial patterns that were not captured otherwise. Table 5 shows the estimated models including a spatial trend.

**Table 5 : results from the probit estimation for the selected RMPs including a spatial trend**

|  |  |  |  |
| --- | --- | --- | --- |
| Variable at farm level (farm household survey) | Orchard | SWC | Irrigation from the river |
| Landholding size | -0.4533335  (0) |  | 1.121603  (0) |
| Landholding size squared | 0.0241578  (0.092) |  | -0.163517  (0) |
| average plot size | 2.406452  (0) |  | -1.850749  (0) |
| Household size/landholding size |  |  | 0.012803  (0.028) |
| female headed HH (binary) |  |  | -0.7546  (0.004) |
| Has hired labor (binary) | -0.0153038  (0) |  |  |
| Access to advise from the extension service (binary) |  | 0.3871204  (0) |  |
| access to credit (binary) |  |  | 0.3200525  (0.004) |
| time to market |  |  | -0.102888  (0.005) |
| time to market sq |  |  | 0.0016409  (0.036) |
| distance to market | 0.063921  (0.004) |  |  |
| distance to market squared | -0.0013686  (0.047) |  |  |
| **X-coordinate** | **-0.2930773**  **(0)** | **0.2908042**  **(0)** | ***0.0334228***  ***(0.562)*** |
| **Y-coordinate** | ***0.0651752***  ***(0.067)*** | **0.1444728**  **(0)** | ***-0.014265***  ***(0.716)*** |
| Constant | 11.04375  (0) | -12.1745  (0) | -2.826954  (0.181) |
| Observations | 683 | 727 | 814 |
| R-squared | 0.1416 | 0.146 | 0.1116 |
| Condition | slope>0 | erosion>0 | at least one flat plot |
| p-value in bracket |  |  |  |

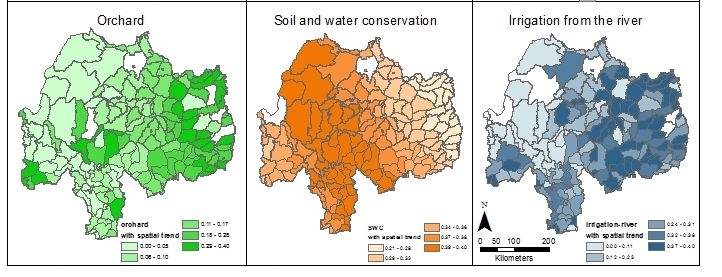
The negative sign of the X value for orchards suggest that willingness of adoption is decreasing as going to the East. The Y-value is not significant and therefore there in no North-South trend in the data. The rest of the model stays relatively similar to the specification without spatial trend, only access to advice is not significant anymore and has therefore been dropped from the equation. Also the explanatory power of the model increases from 0.10 to 0.14 with the spatial trend. The variables for extrapolations at woreda level are the same than for the models without spatial trend. The X and Y coordinates used for extrapolation are the coordinates of the centroid of each woreda polygon. Figure 3 shows that the willingness to adoption has increased in the central part of the basin, compared with the maps resulting from estimation without spatial trend.

|  |  |  |  |
| --- | --- | --- | --- |
| Variable at farm level (farm household survey | Multipurpose tree | Water harvesting | wells |
| Landholding size | 1.0824 |  |  |
|  | 0.001 |  |  |
| Landholding size squared | -0.221442 |  |  |
|  | 0.002 |  |  |
| Offfarm | 0.1510418 |  | 0.805675 |
|  | 0.037 |  | 0 |
| hired labor | 0.0088002 |  |  |
|  | 0.061 |  |  |
| Access to advise | 0.5720423 |  |  |
|  | 0 |  |  |
| distance to market |  |  | 0.331085 |
|  |  |  | 0.014 |
| distance to market |  |  | -0.04236 |
|  |  |  | 0.014 |
| **X coordinate** | **-0.0153421** | ***0.533169*** | **-0.01088** |
|  | **0.82** | ***0*** | **0.912** |
| **Y coordinate** | **-0.0763163** | ***0.172375*** | ***0.248856*** |
|  | **0.091** | ***0.011*** | ***0.002*** |
| Constant | -1.796773 | -24.2862 | -4.90228 |
|  | 0.456 | 0 | 0.12 |
| Observations | 683 | 1000 | 818 |
| Rsquared | 0.1001 | 0.3193 | 0.2232 |
| Condition | slope>0 | no | At least one flat plot |

For multipurpose trees, the coordinates are not significant, suggesting that the other explanatory variables capture the spatial variation well. Consequently, the coefficients of the other explanatory variable only change slightly and can be interpreted similarly to the model without spatial trend.

However water harvesting seems to have a spatial trend that explains all the variation and which increases the explanatory power of model from 0.1 to 0.3. Like soil and water conservation, water ponds, the most commonly promoted water harvesting technology, has been promoted by the Ethiopian government in the years before the survey has been done. This governmental intervention took place in the dryer zones of the basin, which is the North East, which is also reflected by the spatial trend.

Finally for wells only the East West coordinate is significant suggesting that there is a bias of adoption towards the East. This variable seems to capture the spatial variation better than landholding size, numbers of plot and access to advice, as these variables are not significant anymore in the model with spatial trend. Access to market and off-farm income remain in the model with the same interpretations as in the model without spatial trend.



**Figure 3 : willingness of adoption at woreda level, in the Ethiopian Blue Nile Basin, based on probit estimation with spatial trend**

For soil and water management, the spatial trend seems to capture almost all the variation. All other variables except access to advise through extension services are not significant anymore and therefore have been dropped. The positive sign on the X value and Y value suggest that willingness of adoption is likely to increase towards the North East. Also for the model with spatial trend the explanatory power of the model almost tripled. An explanation to this phenomenon can be found in the past and current governmental policies. Indeed, soil and water conservation structures have been implemented in form of mass mobilization in which everyone participated, and therefore individual characteristics do not really influence adoption. In 2005, when the survey was done, mainly the Northern part of the country and therefore also the North Eastern part of the basin had organized these big campaigns, and only the spatial trend can capture this phenomenon.

Finally, for irrigation from the river the spatial trend is not significant, suggesting that the model without the spatial trends captures the variability well.

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**Figure 4 : willingness of adoption at woreda level, in the Ethiopian Blue Nile Basin, based on probit estimation with spatial trend**

Not surprisingly, when the model with and without spatial trend do not differ (i.e. when the coordinates are not significant) the adoption maps look very similar, like for multipurpose trees. In this case the model without spatial trend performs better and should be retained for further modeling.

The water harvesting map reflects the spatial trend only, as there is no other variable in the model. For wells, the spatial trend is significant but does not change the overall pattern of adoption and therefore the two maps look similar. For these two maps it is difficult to say which of the two models performs better.

## Mapping approach

### Mapping suitability and feasibility rainwater management practices

Our suitability maps combine geographic data in order to identify locations where a given practice is suitable and likely to be adopted. The steps we used to develop these maps are shown in Figure 5.

Selection of practices constituting ‘best bet’ RMSs at the landscape scale (A)

Creation of a bio-physical suitability layer (D)

Identification of suitability criteria and thresholds (B)

Creation of criterion maps (C)

Figure 5 : The approach to creating single suitability maps (Module 1)

The first step is to identify and select RMPs (A). It is important that practices are selected that cover the different landscape zones (uplands, midlands and lowlands, grazing land and degraded land) and together form the ‘best bet’ strategies for the landscape. This selection can be based on expert knowledge or on participatory approaches involving key stakeholders from the area.

The second step is to define the suitability criteria of each practice through a literature review, complemented by expert knowledge. For this it is first necessary to identify geographical layers (maps) that represent the criteria and define the range of the suitability criteria (B). For each criterion of suitability, a binary map is created based on existing geographic layers (identified in B), indicating locations where the conditions are met (C). These are referred to as criterion maps. These layers then need to be combined and aggregated into suitability maps. There are two different approaches to combining different suitability criteria into one measure or index of suitability: the overlay approach, which does not necessarily require observations from the ground and the Bayesian approach, which does require observations of RMPs on the ground.

The overlay approaches can involve aggregation techniques based on relatively simple methods: each individual criterion map gets an equal weight, or a weight based on expert knowledge. The method works very well with binary variables, but leads to an implicit weighting when using continuous variables. To introduce continuous data into the aggregation, it needs to first be normalized into a layer of values ranging between 0-1. This normalization implicitly weights the importance of the variable in the overall aggregation. Therefore the individual suitability layers are first transformed into binary criterion maps (C) which are then overlaid on each other (D). With both techniques the weight given to one criterion will change as new criteria are added to the analysis.

Bayesian approaches, which include ‘weight of evidence’ and a Bayesian network, are data-driven methods that ‘learn’ from real observations on the ground (referred to as the evidential theme). This evidential theme is then used to estimate the relative importance of each driver by statistical means (Bonham-Carter, 1994; Zahiri et al., 2006; Deng, 2010). The weight of evidence technique can only be applied to binary data and therefore also uses criterion maps (C). The Bayesian network technique is similar to the weight of evidence method but allows the criterion maps to be correlated (Jensen, 2007; Kemp-Benedict, 2008).

In the past many RMPs have been promoted in Ethiopia, regardless of their suitability. Therefore ground-based evidence might lead to the wrong conclusions. There is an extensive literature that describes the biophysical conditions under which RMPs are likely to be successful . For this reason this paper adopts the approach of aggregating criterion maps into suitability maps, using an equal weight overlay. This choice also helped avoid addressing (potentially) contradictory expert opinions. These suitability maps are then constructed into a binary map that indicates locations that meet all the biophysical conditions for a RMP.

Feasibility maps are maps that take the socio-economic constraints into account and make use of the willingness of adoption maps.

Bio-physical suitability map

Willingness of adoption map

Feasibility map

Figure 6 : procedure to get the feasibility maps (in straight line user-input need for Nile-Goblet)

A feasibility map is the overlay between the bio-physical suitability map (by construction a 0/1 map constructed in the previous step) and the willingness of adoption map (by construction a 0-1 map). As these two are multiplied the resulting feasibility map shows the percentage of adoption of a given RMP in the suitable locations.

### Mapping rainwater management strategies

Up to this point results are suitability and feasibility maps for single RMPs. The procedure of combining single RMPs into RMSs at landscape/watershed scale is presented in Figure 7. The first step is summarizing the pixel-based suitability and feasibility maps into a landscape/watershed scale. The single feasibility maps resulting from the previous step are combined with a landscape layer (A), a shape file that represents the landscape/watershed, to compute zonal statistics. The zonal statistics calculation returns statistical information for each of the landscapes/watersheds, namely the percentage of the area that is suitable based on the suitability maps as well as the average adoption rate on suitable location based on the feasibility maps.

A second step is then what we call a process of “strategy quantification”. Apart from indicating which practices constitute the strategy, a minimum suitability threshold for each these practices is needed. In other words, a quantitative measure is needed to definewhen a practice is important enough to considered suitable or feasible at landscape level. For suitability this is done by defining a minimal area threshold to be fulfilled for each practice forming the strategy. For feasibility, the minimal percentage of adoption on suitable locations of the practices that form the strategy will be retained as adoption rate at watershed level. Applying these thresholds to the watershed summaries calculated in step one then allows for selecting those watersheds that are suitable (or feasible) for the overall RMS.

Strategy quantification (C)

Suitability / feasibility map

practice I

Suitability / feasibility map

practice II

Suitability / feasibility map

practice III

Rainwater management strategy map (D)

Landscape delineation layer (A)

Targets

practice I

Zonal statistics (B)

Targets

practice II

Targets

practice III

Figure 7 : the up-scaling procedure in Goblet (in straight lines user-input for the Nile Goblet)

# Application of the mapping framework to the Ethiopian Blue Nile

## Study area description

The Blue Nile Basin in the Ethiopian highlands is situated in the North West of Ethiopia, as shown in Figure 8, and is considered as an area with high agricultural potential. Annual rainfall ranges from 500-1800 mm which is mostly concentrated in the month of June, July and September. It is a very diverse area with mountainous areas, but also large plains. Whereas in the South West, deep and fertile Nitisols can be found, shallow and erosion prone Leptosols shape the East. Around Tana lake fertile luvisols can be found and the Highland plateau is shaped by heavy clay soils (vertisols). Farming systems are mainly crop based though mixed with livestock, some areas towards the Sudanese borders are considered as agro-pastoral zone.

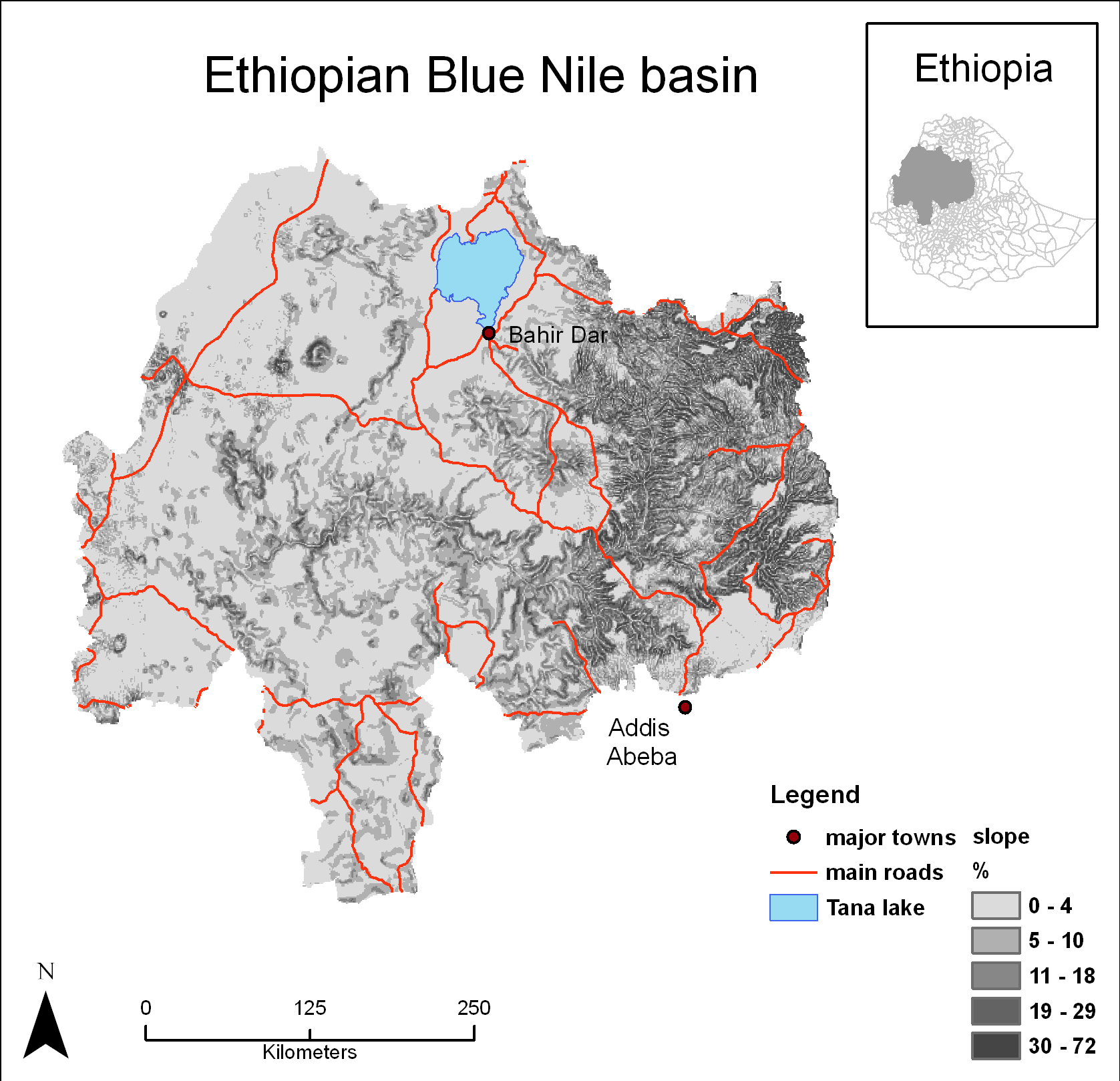


Figure 8: The study area, the Ethiopian Blue Nile with the slope and major roads

Population pressure is pushing more and more young people to move to urban areas looking for jobs, to live as landless livestock owners or to gain new land for agriculture. As a result deforestation is high and the capacity of the landscape to infiltrate water is decreasing. Also grazing land is converted to cropland, increasing the livestock pressure and fodder shortage leading to faster land degradation. Run-off is therefore increased, and erosion on already erosion prone soils in increased. In the whole basin, 32 percent of the area exhibits an erosion rate higher than the critical threshold of 11 ton/ha/year (Haileslassie et al., 2005)

RMPs have been promoted in many areas of the Blue Nile basin (Merrey and Gebreselassie, 2010). Soil and water conservation are promoted in form of “mass mobilization” where communities build bunds and terraces together regardless of the ownership of the land (Harrison, 2002). This approach has in the past mainly been applied to the North but is more and more applied also to other regions in the Blue Nile Basin. Despite of the fact that most of the smallholders seem to be in favor of soil and water conservation, in many locations the structures are not well maintained and useless after a couple of years. Water harvesting ponds have been aggressively promoted by the governmental extension service in the dryer area of the basin, but most of them have been abounded within years (Amha, 2006; Merrey and Gebreselassie, 2010).

## Selection of best bet practices

GIZ is active in some 45 woredas (districts) of the basin, promoting integrated approaches. GIZ priority RMPs, for which most of the funds are invested in 2011 are among others, fruit tree orchards (mainly apple and mango), soil and water conservation structures (terraces and bunds), water harvesting infrastructures (ponds, cisterns), small scale irrigation (river diversion, pumps) and gully rehabilitation (personal communication,2012). GIZ also invests in other practices, some of them are in fact part of a farm scale strategy and can only be implemented in conjunction with another practice at farm scale. For example beehives should be adopted by farmers with fruit trees. Also some practices are applicable everywhere in the basin, such as fertility management. Not mapping them does not mean that these practices are not important, but there is no need for separate targeting.

The final set of best –bet practices chosen are : mango trees, apples trees, multipurpose trees, bench terraces, hillside terraces, stone bund, soil bund, wells, river diversion, grazing land management and gully rehabilitation. Each of these practices has a well-defined suitability range described in literature.

In the perspective to assess the hydrological impact of implementing the different rainwater management practices, the suitability maps, the feasibility maps and the strategy maps need to be prepared in such a way that they can be introduced into SWAT as a scenario. Most of these practices cannot be modeled separately by SWAT (Santhi et al., 2006). Therefore some of these practices have been aggregated to a higher level as presented in Figure 9. Mango and apple trees are summarized into orchard, both type of terraces and bunds, respectively into terraces and into bunds, also referred to as strips in SWAT modeling respectively.

Figure 9 : aggregation of practices for hydrological modeling in SWAT

Mango

Apple

Hillside terraces

Bench terraces

Soil bund

Stone bund

Multipurpose tree

River diversion

Gully rehabilitation

Initial set of practices

Practices for SWAT modeling

Orchard

Grazing land management

Wells

Multipurpose tree

Terraces

Bunds/strips

River diversion

Wells

Gully rehabilitation

Grazing land management

Water harvesting

Water harvesting

## RMS practice mapping

### Specifications used for the suitability and feasibility mapping

In order to produce the suitability maps, a broad literature review helped to identify the suitability thresholds. These thresholds have been confirmed by experts through various stakeholder consultations. The retained thresholds are presented in Table 6, as well as the geographical layers and corresponding adoption maps.

Table 6 : suitability condition for the selected practices, the geographical layers used and the corresponding adoption map

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Practice | Suitability condition | Geographical layer |  | Adoption map |
| Apple tree | Minimum temperature below 12c (Carter, 2007) Not on sandy soil, not on leptosol, not on vertisol, not on regosol, not on cambisol, not on swamps (Carter, 2007) Rainfall >1400 mm (Carter, 2007) Not on highly degraded land  Not on forest, not on settlements | temperature soil   rainfall land degradation |  | Orchard |
| Mango trees | Rainfall > 800 mm (Griesbach, 2003) Not on sandy soil, not on leptosol, not on vertisol, not on regosol, not on cambisol, not on swamps (Griesbach, 2003) Not on highly degraded land(Griesbach, 2003) Annual average temperature > 20 (Griesbach, 2003) Not on forest, not on settlements | rainfall  soil  land degradation temperature land use |  | Orchard |
| Multipurpose tree | Rainfall 500-2000 (Reubens et al., 2011) Crop land,  medium and high degradation | rainfall land use land degradation |  | Multipurpose tree |
| Bench terracing | Rainfall < 1400mm (Desta et al., 2005) Not on vertisol, not on leptosols, not on regosols Slope between 12-58% (Desta et al., 2005) Not on forest, not on settlements | rainfall soil elevation land use |  | Soil and water conservation |
| Hillside terracing | Rainfall < 900mm (Desta et al., 2005) slope 10- 50% (Desta et al., 2005) Not forest not settlements | rainfall elevation land use |  | Soil and water conservation |
| Soil bund | rainfall < 1400 mm (Desta et al., 2005) slope 3-15% (Desta et al., 2005) OR rainfall > 1400mm if graded (Desta et al., 2005) slope 3-15%(Desta et al., 2005) soil ≠ leptosol, vertisol, leptosols, regosols (Desta et al., 2005) not degraded land (Desta et al., 2005) | rainfall  elevation  rainfall  elevation soil  land degradation |  | Soil and water conservation |
| Stone bund | rainfall < 1400 mm (Desta et al., 2005) slope 5-35%(Desta et al., 2005) OR rainfall >1400 (Desta et al., 2005) slope 5-35%(Desta et al., 2005) soil not leptosol, not vertisol, not on cambisol, not on swamps (Desta et al., 2005) | rainfall  elevation  rainfall elevation soil land use |  | Soil and water conservation |
| River diversion | 2.5km around perennial river soil not sandy soil | river soil |  | Irrigation from the river |
| Well | very shallow + shallow aquifers (Desta et al., 2005) slope < 35% (Desta et al., 2005) soil ≠ leptosol (Desta et al., 2005) | groundwater elevation soil |  | Wells |
| Gullies | Normalized topographic index between 0.8-1  soil not lepsol, not regosol, not on swamps and not on waterbodies not on forest area or settlement | topo. index soil land-use |  | Soil and water conservation |
| Controlled grazing | Grassland | land use |  | No |
| Water harvesting | No forest aridity index 0.02-0.65 (semi-arid zones) | land use aridity index |  | Water harvesting |

### Suitability maps for the best-bet practices

The suitability maps according to the criteria shown in Table 6 are then aggregated into the SWAT practice layers as illustrated in Figure 9. Some of these practices are competing, i.e cannot be implemented at the same time on the same location. For example, it is not possible to have a soil bund and a terrace or a multipurpose tree and a fruit tree on the same location. For modeling scenarios into SWAT, one needs to correct the layer, and assign one of the two practices to a given pixel (see 4.3.4 for detailed explanations on the correction).

D:\Ilri\suitability 2\paper\mango.tifD:\Ilri\suitability 2\paper\multipurpose tree.tif

Figure 10 : suitability maps for apple tree (left), for mango tree (middle) and multipurpose tree (right)

Mangoes are suitable in the low lands in the West of the basin, whereas apples are suitable in the in the highland in the central part of the basin as shown in Figure 10. Multipurpose trees are mainly suitable in the Eastern part of the basin.

D:\Ilri\suitability 2\paper\gullies.tif

Figure 11 : suitability maps for hillside terraces (left), for bench terraces (middle) and gullies (right)

As shown in Figure 11, terraces are most suitable on the steeper slopes which are mainly located in the Western part of the basin. Gullies can be found in the flatter areas and therefore more in the central part of the basin



Figure 12 : suitability maps for stone bunds (left), soil bund (middle) and grazing land management (right)

Similarly to terraces stone and soil bunds are more suitable in the Western part of the Basin as shown in Figure 12. Grassland management is mostly found on two spots, one in the center of the basin and the other in the South West.

D:\Ilri\suitability 2\paper\wells.tif

Figure 13 : suitability maps for wells (left), river diversion (middle) and water harvesting (right)

Figure 13 shows that wells are most suitable in the West of the basin. River diversion is mostly suitable in the South of the basin where the rivers are. Finally water harvesting is suitable in the semi-arid areas, which are the lowlands of the basin.

### Feasibility maps for the best-bet practices

In order to create feasibility maps, adoption maps need to be overlaid with the suitability maps. As adoption maps are usually run for a category of practices, the same adoption map can be applied to several practices. Table 7 shows which adoption map has been used for which practice.

Table 7 : linking adoption maps to practices

|  |  |  |
| --- | --- | --- |
| Adoption map | Better model (based on R squared and significance of the spatial trend) | Can be used with practice |
| Orchard | With spatial trend | All types of fruit trees (mango, apple) |
| Multipurpose tree | Without spatial trend | All type of multipurpose trees |
| Soil and water conservation | With spatial trend | All type of soil and water conservation (terraces, bunds, gullies) |
| Irrigation from the river | Without spatial trend | Irrigation from the river (pump, diversions) |
| Wells | With spatial trend | Wells |
| Water harvesting | Without spatial trend | Water harvesting, ponds, cisterns |
| None |  | Others |

D:\Ilri\suitability 2\run6\TIFFs\apple.tif D:\Ilri\suitability 2\run6\TIFFs\mango.tif D:\Ilri\suitability 2\run6\TIFFs\mp_tree.tif

Figure 14 : feasibility maps for apple tree (left), for mango tree (middle) and multipurpose tree (right)

Figure 14 show that apples and mango are most likely to be adopted in the center of the basin, whereas multipurpose trees are most likely to be adopted in the South East.

D:\Ilri\suitability 2\run6\TIFFs\hillside.tif  D:\Ilri\suitability 2\run6\TIFFs\gullies.tif

Figure 15 : feasibility maps for hillside terraces (left), for bench terraces (middle) and gullies (right)

Figure 15 shows that hillside terraces are more likely to be adopted in the South of the basin, whereas gullies occur less in the West then in the rest of the region

D:\Ilri\suitability 2\run6\TIFFs\stone.tif D:\Ilri\suitability 2\run6\TIFFs\soil.tif

Figure 16 : feasibility maps for stone bunds (left), soil bund (right)

Figure 16 shows that stone bunds are more likely to be adopted in the South West of the Basin, whereas soil bunds have a higher adoption rate in the West of the basin and in the South East.

D:\Ilri\suitability 2\run6\TIFFs\river.tif D:\Ilri\suitability 2\run6\TIFFs\water harvesting.tif

Figure 17 : feasibility maps for river diversion (wells) and water harvesting (right)

Figure 17 shows that irrigation from the river is more likely to be adopted in the Western part of the basin. Water harvesting is more likely to be adopted in the Easter part of the basin. Note that the feasibility map for wells resulted into an empty map and is therefore not presented here.

### Suitability maps for the best-bet practices for SWAT

River diversion wells, gully rehabilitation and water harvesting are not practices for which any aggregation or correction has been a performed on in order to fit SWAT modeling. These maps can be directly taken from the practice modeling.

Mango and apple have been aggregated into orchards and corrected, to insure that no pixel is assigned to both orchards and multipurpose trees.

Furthermore, the strip layer is the aggregation of stone bunds and soil bunds and the terraces layer is the aggregation of hillside terraces and bench terraces. In addition, these two layers have been corrected to insure that terraces and bunds are not assigned to the same cell.



Figure 18 : suitability for corrected orchard (mango + apple), corrected multipurpose tree



Figure 19 : suitability for corrected terraces (hillside terraces + bench terraces), corrected bunds (soil bunds + stone bunds)

### Feasibility maps for the best-bet practices for SWAT

These maps can also be overlaid with the adoption maps, resulting into feasibility maps for these aggregated practices.

C:\Documents and Settings\cpfeifer\Local Settings\Temp\wzd96f\orchards.tifC:\Documents and Settings\cpfeifer\Local Settings\Temp\wz803e\mptree.tif

Figure 20 : feasibility for corrected orchard (mango + apple), corrected multipurpose tree

C:\Documents and Settings\cpfeifer\Local Settings\Temp\wz09a2\terraces.tifC:\Documents and Settings\cpfeifer\Local Settings\Temp\wz3b9f\bunds.tif

Figure 21 : feasibility for corrected terraces (hillside terraces + bench terraces), corrected bunds (soil bunds + stone bunds)

### Discussion on suitability and feasibility mapping in the Blue Nile

Maps presented in the previous sections have to be taken with caution. Indeed, some of the maps might not reflect the reality on the ground as their accuracy depends fully on the accuracy of the input data. In two particular cases, this accuracy is a real problem.

Firstly, the wells map is based on the groundwater map and therefore particularly problematic. Indeed, this groundwater map is based on the geological subtract which is a pretty rough proxy for groundwater access. In a validation procedure, comparing the prediction of the map with the practices wished by the community, 100% of the prediction were wrong, suggesting that a much more detailed map would be needed. Also the adoption map for wells is based on a pretty low number of adopters, which makes the map very unreliable, leading to an empty feasibility map. Therefore we advise to not use the wells maps presented in this report.

Secondly, during the validation procedure, more perennial rivers where identified by the communities than by our maps, also suggesting that the river map is not very accurate. When using our river diversion map, one should keep in mind that there might be many more locations where irrigation from the river might be possible.

In general, validation on the ground has shown that predictions with this mapping approach underestimate suitable and feasible areas for most technologies, mainly due to the lack of detailed input data.

## Strategy mapping

### Approach chosen for combining practices into strategies

In principle, a strategy is any combination of practices that ensures that the joined objectives of water infiltration (up-zone), water and soil conservation (mid-zone) and more efficient use of water (low-zone). A two-step approach is used to assign a strategy to a watershed. In the first step, practices wich meet the strategy quantification criteria (i.e that meet the minimal area threshold for suitability or the minimum adoption threshold for feasibilty). In a second step, one needs to check if these practices can be combined in such a way there is at least one practice per zone. Many combinations are possible, potentially 216 combinations[[2]](#footnote-2) . In principle there are 8 core strategies[[3]](#footnote-3) that are strategies that ensure that at least one practice is adopted in each zone. All the other combinations are a more complicated subset of these core strategies. For example orchards could be combined multipurpose tree within the up-zone, or orchards can be combined with water harvesting.

In order to reduce the strategies mapping procedure to a handy numbers of maps, the approach chosen for this report is to look at the most complicated strategy only for each of the watersheds. For the purpose of this paper, the SWAT watersheds have been used as landscape layers. For the strategy quantification, a 10 % of the area threshold was applied to all practices except gullies and river diversion where a threshold of 2% has been retained. With these settings, only 9 “most-complicated” combinations for the Blue Nile are possible. They are shown in Table 8. For more than half of the watersheds, no combination that combines practices for the 3 zones is possible.

Table 8 : strategies in the Blue Nile based on 10% threshold for all practices except river diversion and gullies for which 2% has been used.

|  |  |  |
| --- | --- | --- |
|  | Strategy | Count in the Blue Nile |
| 0 | No | 26 |
| 1 | orchard, multipurpose tree, strip, river diversion, well, gully rehabilitation, water harvesting | 7 |
| 2 | orchard, multipurpose tree, strip, river diversion, gully rehabilitation, water harvesting | 4 |
| 3 | multipurpose tree, terraces, strip, river diversion, gully rehabilitation, water harvesting | 4 |
| 4 | multipurpose tree, strip, wells, water harvesting | 1 |
| 5 | multipurpose tree, strip, river diversion, gully rehabilitation, water harvesting | 1 |
| 6 | multipurpose trees, orchard, terraces, strips, river diversion, gully rehabilitation, water harvesting | 1 |
| 7 | orchards, multipurpose tree, strip, well, grazing land management, gully rehabilitation, water harvesting | 1 |
| 8 | multipurpose tree, strip, river diversion, well, grazing land management, gully rehabilitation, water harvesting | 1 |
| 9 | orchards, multipurpose tree, strip, river diversion, well, grazing land management, gully rehabilitation, water harvesting | 1 |
| 10 | multipurpose tree, terraces, strip, river diversion, well, grazing land management, gully rehabilitation, water harvesting | 1 |

C:\Users\Catherine\Documents\geodata\CPWF_data\strategy.tif

Figure 22 : strategy map showing the location of the strategies identified in Table 8

SWAT makes use of so-called hydrological response units. These are very small units defined by land-use and slope. Strategy maps at watershed level are therefore difficult to introduce into the SWAT model. However SWAT can easily handle grid cell data, as these can be aggregated into the hydrological response unit. As a result, maps are needed that capture suitability and feasibility maps in watersheds where the practices are part of a strategy.

In principle one could produce a set of maps for each strategy capturing the suitability or the feasibility of each practice forming the strategy. This approach would result in an unmanageable amount of layers. To reduce the amount of layers, it is possible to create one map per practice showing where the practice is suitable (or feasible) and part of any strategy presented in Table 8[[4]](#footnote-4). By using the combination all the practice maps, one can model all the strategies in one go into SWAT. In summary, for each practice, four maps are produced. They are described in Table 9.

Table 9 : different maps produced for each practice

|  |  |  |  |
| --- | --- | --- | --- |
| Different maps | | Suitability | Feasibility |
| General |  | suitability map | feasibility map |
|  |  |  |  |
| As part of a strategy | | Suitability as part of a strategy map | Feasibility as part of a strategy maps |

### Strategy map for SWAT modeling



Figure 23 : suitability maps as part of a strategy for orchard (left), multipurpose tree (middle) and grazing land management (right)



Figure 24 : suitability as part of a strategy maps for terraces (left), for bund (middle) and gullies (right)



Figure 25 : suitability as part of a strategy maps for wells (left), river diversion (middle) and water harvesting (right)



Figure 26 : feasibility maps as part of a strategy for orchard (left), multipurpose tree (middle) and grazing land management (right)



Figure 27 : feasibility as part of a strategy maps for terraces (left), for bund (middle) and gullies (right)



Figure 28 : feasibility as part of a strategy maps for river diversion (left) and water harvesting (right)

### Discussion on the rainwater management strategies of the Blue Nile

From all possible combinations of rainwater management strategies only 10 combinations seem to be applicable to the Blue Nile, whereas almost half of the watersheds have no possible combination. This suggests that integrated rainwater management is often not possible in the Blue Nile. But this result is driven both by the accuracy of the suitability maps as well as the landscape delineation layer. As discussed previously, the input layers for the suitability maps are not always very accurate and the validation exercises in the fields have shown that our maps underestimate the real potential. Therefore, we might also underestimate the suitable watersheds for the strategies.

Secondly, the landscape definition layer, in this case the SWAT watersheds define the area within which a strategy should be applied. It can be seen that only for smaller watersheds no strategy could be identified. Using another landscape definition might lead to different results, suggesting that there is a scaling issue. It is therefore important to choose a landscape delineation layer that carefully takes the objective of the maps into account.

# Technical discussion of the framework

This report has presented a modeling framework to identify suitable landscapes for implementing RMSs at landscape scale, based on biophysical and socio-economic criteria. This section discusses some of the limitations of this framework. It begins by discussing the limitations linked with the availability of geographical layers, and the technicalities linked to the adoption maps. Finally, it discusses how to make practical use of the maps, including suggestions on how to connect the results from this framework with impact assessments.

## Limitations linked to the availability of geographical layers

The suitability maps are based on relatively simple indicators, for which geographical layers exist. As such, the accuracy of the suitability maps directly depends on the accuracy of the input maps. Many continent-wide geographical layers were used in our examples. These lack accuracy at the local level and our results should therefore be treated with some caution.

Secondly, the chosen thresholds might not capture the complexity of a RMP and might therefore over predict suitable areas. For example, the suitability of river diversions depends not only on proximity to a perennial river, but also on the amount of water in the river and ease of access to it.

This report is an illustration of a mapping framework and has used the geographical layers that were available to us. For example the groundwater map,which is based on geological subtracts only. It has not been validated with fielddata. For our field work we know this map perform pretty badly but it is the only map currently available for Ethiopia.

The model can easily be rerun when more accurate geographical layers become available. With the increased use of GIS it is likely that more detailed geographical layers will permit future modeling exercises to identify suitability in more detail and capture more of the complexity of RMPs. Finally, in this study we have applied the framework to a relatively large study area. In principle, it could be applied to smaller areas, where more geographical layers with higher accuracy might be available or could be created for this specific purpose.

## Technical issues linked to the adoption layers

Because the adoption maps are developed to extend geographical targeting based on bio-physical data, the adoption models do not contain any bio-physical variables. Only some bio-physical variables have been used to constrain the full sample of farmers to a subset of farmers that are likely to have the right bio-physical conditions to adopt a given practice. Using only a sub-set of the farmers and excluding bio-physical variables decreases the explanatory power of the different models. In addition to that only variables that are both in the farm household survey and available as geographical layer (census data) can be used. Especially in a developing world context where only few datasets are representative at high resolution, this limits the number of variables that can be included considerably. Therefore, regressions for small area estimation have always a lower explanatory variable than classical modeling approaches.

Classical adoption analysis, i.e. not meant for a small area estimation, based on the same farm household survey suggests that age of the head of the household, religion, access to aid, welfare indicators (corrugated roof, concrete houses) or the average distance from the plot to the farmstead can explain adoption of some of the rainwater management practices (Defourny, 2012). These variables have been omitted as no census data or geographical layer is available for extrapolation, which might result into an omitted variable bias.

All socio-economic variables have spatial patterns: for example, small fragmented landholdings are more likely to be found in densely populated area, which are more likely to be in high potential areas. For all the omitted variables mentioned above, except the corrugated roof, the hypothesis of a spatial trend could not be rejected. Consequently, introducing a spatial trend into the models allows capturing the variability of omitted variables and correcting for the omitted variable bias. Also the explanatory power of the model with the spatial trend increases. For soil and water conservation it tripled, suggesting that these models capture more of the variability and explain the adoption better.

## Using the maps

The example presented in this paper only models three practices per zone but this could easily be extended, allowing for an exponentially higher number of combinations of practices and strategies. It is likely that, in some locations, more than one practice is possible and therefore practice suitability maps and landscape scale strategy maps could show a ‘menu of options’ rather than predicting what is actually happening, or should happen, on the ground. These maps could show the extent of contextual differences in watersheds and therefore contribute to the geographical targeting of practices and strategies.

These maps, showing the different options available within a particular watershed, can provide a starting point for a dialogue with communities about improving water management. Community involvement is crucial for three main reasons. Firstly, there is a high level of uncertainty about the accuracy of the maps and community involvement is a key way to use local knowledge to validate them. Secondly, some strategies might not bring any benefits to those adopting them, or the benefits may only be long-term. Orchards are an example: one needs to wait five to ten years before harvesting the fruit. Involving communities in a participative way can lead to the adoption of innovative benefit-sharing mechanisms, from which the community as a whole can benefit. Thirdly, some strategies might not be implemented because the area is missing some crucial elements that were not mapped and thus were excluded from the modeling approach. Examples might include the lack of access to a specific input market or lack of knowledge. Such problems typically cannot be solved by the farmers themselves and might require interventions from other stakeholders, such as government or NGOs. These interventions can be more readily identified by involving the community through e.g. rapid rural appraisal tools..

## NBDC Tools to complete the modeling framework

As companions to this modeling framework two tools have been developed to make the approach more tangible and the maps more useful, namely the Nile Goblet tool and the happy strategy game.

### Nile Goblet tool

The Nile Goblet tool is an open source GIS tool. It is based on the modeling framework presented in this report. It allows policy-makers, researchers and extension services to produce the suitability maps, the feasibility maps and the strategy maps with the thresholds they believe to be the correct ones without any prior GIS skills.

This tool is very flexible and allows adding new geographical layers. Also it allows for selecting the scale one wants to work at. If detailed data are available for a micro-watershed, very accurate high resolution suitability and feasibility maps can be produced.

### The happy strategy game

However accurate the maps can be, no practice should be implemented without understanding the wishes of and the limiting factors in a community. The “happy strategies game”, developed for the NBDC, consists of a set of cards describing rainwater management practice that participants combine and match to the context of a specific landscape. This game can be adjusted for communities and be used as a rapid rural appraisal tool to understand the communities’ wished watershed management and necessary interventions. Through the discussion with the communities about why some of the practices suggested by the modeling framework presented in the report are not adopted, one might identify new entry points to improve water and soil management. More information about the happy strategies game can be found under [www.happystrategies.wikispaces.com](http://www.happystrategies.wikispaces.com) .

# Conclusion

This report presents an approach to develop maps that indicate where which rainwater management is suitable in the Blue Nile, both from a bio-physical and socio-economic perspective. The integrated water management concept suggests that rainwater management practices should be implemented in different combinations, therefore the presented approach proposes a framework to aggregate suitability of different rainwater management practice at the landscape scale.

This report has shown where which rainwater management practice is suitable and how it should be combined with others in order to manage watersheds in their integrity. The maps show that there is a suitable rainwater management practice for every location in the Blue Nile. There are more practices possible in the highlands in the center and the East of the Basin then in the lowlands in the West. When combining them into strategies with at least one RMP per zone we can see that the most eastern part, as well as the Northern part of the Blue Nile Basin is not suitable for any combination or rainwater management strategy.

The maps resulting from the modeling framework presented in this report are far from being perfect; data is inaccurate, thresholds are based mainly on expert knowledge not on evidence and the resolution is quite low. Therefore, the modeling framework comes with a set of tools that should make the framework more tangible for the non-scientific community and address some of the limitations. Nonetheless, these maps are useful to remind policy-makers and extension services that there is no silver bullet, and rainwater management is site specific.

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1. In the probit case, general residual as defined in Gourieroux (1987) should be modeled. [↑](#footnote-ref-1)
2. We have 2 best-bet practices for each of the zone. In combination with the potential of not applying any practice in a specific zone this gives 3 combinations in each of the 3 zones = 33 = 27 combinations. The three practices that are not connected to any zone give us23 = 8 potential combinations of practices not connected to any zone. In total there are therefore 27 \* 8 = 216 potential strategies. [↑](#footnote-ref-2)
3. at least one of the two practice in each of the 3 zones, i.e. 23 = 8 combinations [↑](#footnote-ref-3)
4. Mathematically, a strategy map per practice is produced. This binary map shows in which watershed the practice is part of strategy and multiply this map with the practice suitability map or the practice feasibility map. [↑](#footnote-ref-4)